Forced vibration tests of compacted gravel-sand

Les essais de vibration forcée d'un sable graveleux compacté

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SYNOPSIS: Forced vibration tests are conducted by exciting a square foundation block with a servo-hydraulic actuating system. Vertical and horizontal vibrations are generated. Three methods are applied to estimate the dynamic characteristics of the tested soil. The shear-wave velocity is obtained by measurements of the surface waves generated by the foundation block. The influence of the contact pressure level on the dynamic characteristics of the soil is investigated.

1 INTRODUCTION

Design procedures for a dynamically loaded foundation require an analysis of the dynamic response of the soil-foundation system. There are two principal methods of analysis. The first one is based on the theory of elastic subgrade reaction. The soil is replaced by elastic springs which produce an equivalent reactive force. Uniform distribution of the subgrade reaction for vertical vibration is assumed. For preliminary design of foundations design values for the coefficient of elastic uniform compression are recommended (Prakash 1981). The second method is based on the linear elastic half-space theory. The half-space is considered to be a homogeneous, isotropic, elastic semi-infinite body. The parameters needed to describe the properties of this elastic body are the shear modulus G, the mass density $\rho = \gamma/g$, and the Poisson's ratio ν. The base of the vibrating footing is generally assumed to be circular. Equivalent lumped parameter models are developed that give approximately the same response curves as the elastic half-space theory (Richart 1970).

A reliable dynamic response analysis of the soil-foundation systems can be achieved, if the dynamic soil properties are known. A variety of field and laboratory methods are developed for their estimation. However, the test data for different methods do not give equivalent design characteristics for dynamic analysis. There are many factors affecting the proper estimation of the soil properties.

The investigation, discussed in this paper, was carried out in connection with a project for a heavy turbine foundation. The 11 m in depth soft ground of the construction site was excavated and replaced by gravel-sand, compacted in thin layers by means of a vibrating roller. Forced vibration tests were conducted to obtain the dynamic characteristics of the compacted gravel-sand. Particular attention was paid to the effect of the contact pressure level on the stiffness and the damping coefficients.

2 EXPERIMENTAL PROCEDURE

The forced vibration tests were conducted with a 3.20x3.20x0.50 m reinforced concrete foundation block. It was additionally loaded by three pairs of reinforced concrete beams with dimensions - 4.00x0.60x0.50 m. The total mass of the foundation block together with the exciting machine was 14.7 t. The mass of the beam was 3.0 t. The base area A of the foundation was approximately 10 m². Resonance test procedures were carried out for each one of the four contact pressure levels. They were 14.7, 20.7, 26.7, and 32.7 kPa respectively. Two positions of the foundation block were selected.

The forced vibrations were realized by a servo-hydraulic actuating system, specially developed for full-scale vibration tests of buildings using Instron company standard units. The system was designed with two ± 50 kN servo-hydraulic actuators, two 45 l/min air cooled power packs and an electronic servo-control console with a two-phase function generator. The inertia forces were generated by moving the attached masses to the actuators piston roads.

The test programme included vertical and horizontal vibration tests. The setup for a vertical vibration is illustrated in Fig. 1. The two actuators were mounted on the top of the foundation block to generate purely vertical vibrations. Six acceleration pickups were fixed on the block to measure its vertical vibration during the resonance tests. The second and the third locations of the pickups (Fig. 1c and 1d) were designed to measure the surface wave propagation. Two of the accelerometers were placed on the top of the foundation block and the other four were fixed on the surface of the soil.

The horizontal vibrations were generated by one of the actuators (Fig. 2). The pack of the steel plates, attached to the piston roads, were fitted with roller bearings. The excitation was adjusted in the direction of one of the foundation block axes. The resulting vibration of the block was due to simultaneous sliding and rocking motion.

The vibration measurements were performed by a multichannel measuring system of the HBM company. The signals from each B12 accelerometers were filtered by a TP3554 low pass filter, amplified by a KWS3073 amplifer, and recorded on a Honeywell visicorder oscillograph.

The resonance frequencies were preliminarily determined by sweeping the frequency of excitation and monitoring the Lissajous figure on the

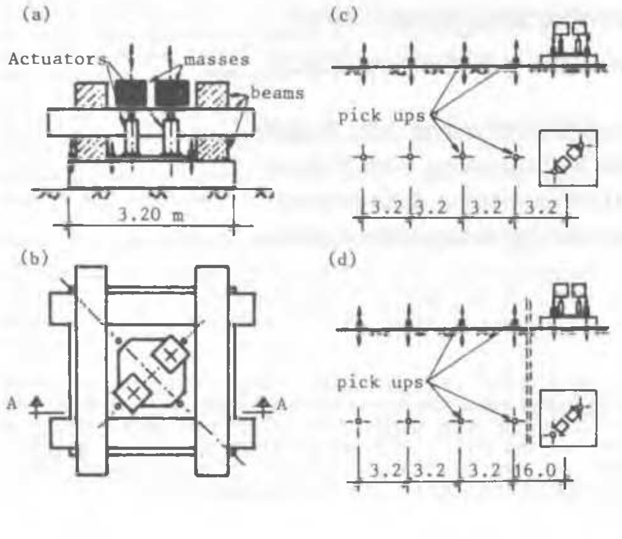

Figure 1. Setup for a forced vertical vibration test. (a) Section A-A. (b) Plan view. (c) and (d) Locations of acceleration pickups for surface-wave measurements.

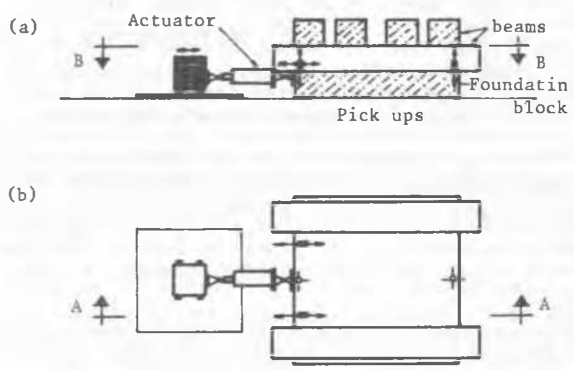

Figure 2. Setup for a forced horizontal vibration test.

oscilloscope screen. In order to obtain the frequency-response curves, the frequency was increased in small steps in the vicinity of the resonance frequencies. Sufficient time was given to the vibration response to become steady-state for each particular value of the exciting frequency. Then the signals from the accelerometers were recorded. The frequencies were measured by a digital measuring unit with an accuracy of 0.01 Hz.

3 DYNAMIC CHARACTERISTICS OF THE SOIL

One of the models frequently used in dynamic response analysis of soil-foundation systems is a lumped-parameter linear elastic model. If a vertical exciting force acts through the gravity centre of the foundation, it will produce a motion with a single-degree-of-freedom. The equation of motion for vertical harmonic excitation of a single-degree-of-freedom system is

$$m\ddot{z} + c\dot{z} + k_z z = F_z \sin\theta t, \qquad (1)$$

where m = mass of foundation and machine,
c = damping coefficient,
k = equivalent spring constant of the soil in vertical direction,
z, $\dot{z}$, $\ddot{z}$ = displacement, velocity and acceleration respectively of the mass in vertical direction.

The natural frequency of the system, neglecting damping, is

$$\omega = \sqrt{k_z/m}\,. \qquad (2)$$

An amplitude-frequency response curve can be obtained by a forced vibration test and the corresponding peak amplitude frequency can be estimated. Assuming a small value of damping, the natural frequency of the system is approximately equal to the peak amplitude frequency. The mass of the foundation block and the exciting machine can be calculated with sufficient accuracy and the equivalent spring constant of the soil can be evaluated by Eq.(2).

The test values of the resonance frequencies in Hz and the corresponding spring constants are given in Table 1.

The coefficient of the elastic uniform compression C_z is calculated by the following relation

$$C_z = k_z/A\,. \qquad (3)$$

where A is the contact area between the foundation and the soil.

A convenient way of expressing damping in a single-degree-of-freedom system is by the damping ratio ξ

$$\xi = c/c_c, \qquad (4)$$

where $c_c = 2\sqrt{km}$, critical damping.

The values of the equivalent damping ratio are determined by the amplitude-frequency response curves, using the following equation of the bandwidth method

$$\xi = (f_2 - f_1)/2f_r, \qquad (5)$$

where f_1, f_2 = frequencies at which the amplitude is equal to $A_{max}/\sqrt{2}$
A_{max} = maximum amplitude
f_r = resonance frequency at which the amplitude is maximum.

One of the experimentally determined amplitude-frequency response curve is presented in Fig. 3. It is normalized by assigning a value of 100% to the maximum measured amplitude.

The maximum amplitude of the steady-state vibration of a single-degree-of-freedom system is

$$A_{zmax} = \mu F_z/k \qquad (6)$$

in which μ is the dynamic magnification factor. For the resonant frequency μ is approximately equal to $1/2\xi$. Measuring F_z and the corresponding A_{zmax} during the test, the damping ratio can be evaluated by the following equation

$$\xi = F_z/2k_zA_z\,. \qquad (7)$$

The values of ξ, obtained by Eq.(7), are also

Table 1. Dynamic characteristics of the soil

Position	Pressure level kPa	Resonance frequency Hz	Spring constant k_z, MN/m		Damping ratio ξ			
			Eq.(2)	Eq.(13)	Eq.(5)	Eq.(7)	Eq.(14)	Eq.(11)
1	14.7	26.0	392	400	0.123	0.563	0.553	0.829
	20.7	26.4	570	576	0.095	0.429	0.424	0.698
	26.7	27.7	809	828	0.063	0.357	0.349	0.615
	32.7	26.2	886	883	0.057	0.523	0.502	0.556
2	14.7	27.9	452	432	0.093	0.624	0.598	0.829
	20.7	29.0	687	689	0.086	0.765	0.762	0.698
	26.7	30.8	1000	1015	0.099	0.650	0.641	0.615
	32.7	29.4	1116	1125	0.081	0.693	0.693	0.556

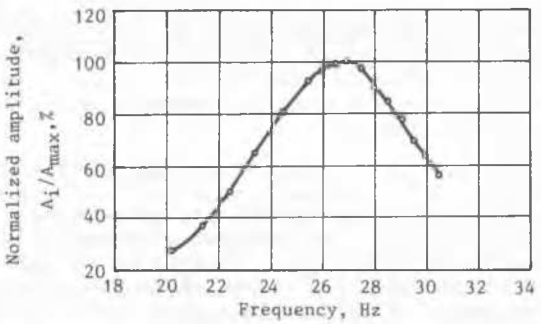

Figure 3. Amplitude-frequency response curve

presented in Table 1.

The model of the soil-foundation system based on the elastic-half-space theory is more rational, but relatively more complicated for practical analysis. Therefore, the Lysmer's analog (Lysmer 1966) which gives close agreement between the elastic-half-space theory and the mass spring-dashpot system is widely used in practice.

The equation of motion for vertical vibration of a rigid circular footing according to Lysmer is

$$m\ddot{z} + \frac{3.4r^2}{1-\nu}\sqrt{\rho G}\,\dot{z} + \frac{4Gr}{1-\nu}z = F_z\sin\theta t. \tag{8}$$

where r = radius of the footing
$\rho = \gamma/g$, mass density of the elastic body
G = shear modulus
ν = Poisson's ratio

Eq.(8) is similar to Eq.(1)
where

$$c = \frac{3.4r^2}{1-\nu}\sqrt{\rho G} \quad \text{and} \quad k = \frac{4Gr}{1-\nu}. \tag{9}$$

To evaluate c and k it is necessary to know the values of the elastic constants G and ν.

The shear modulus G is obtained from the test data for the shear-wave velocity v_s by the following relation

$$G = \rho v_s^2. \tag{10}$$

The mean value of the shear-wave velocity is determined by surface-wave propagation measurements. The phase angle-versus-distance to the foundation block is plotted as shown in Fig. 4. The wavelength λ of the propagating waves are determined from that relation. The average mass density of the compacted gravel-sand is ρ = 1.72 t/m³. The Poisson's ratio is chosen to be 0.3.

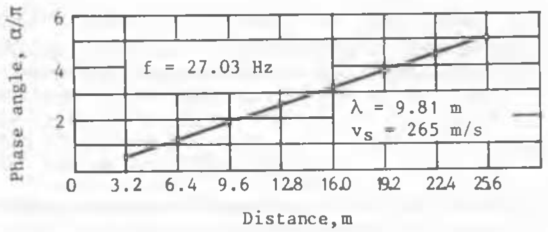

Figure 4. Phase angle-distance relation

The damping ratios are calculated by the following equation

$$\xi = 0.425/\sqrt{B_z}, \tag{11}$$

where

$$B_z = \frac{1-\nu}{4}\frac{m}{\rho r^3}. \tag{12}$$

The equivalent radius r of the square founation block, used in the tests, is determined by equating its contact area to an area of a circular footing.

The mean value of the shear-wave velocity from all tests is v_s = 260 m/s. The shear modulus and the spring constant corresponding to this value are G = 117 MPa and k_z = 1200 MN/m, respectively. The values of ξ are given in Table 1.

Another method for determination of dynamic characteristics of soils by field tests is proposed in the Manual for design of machine foundations, 1982, called "transfer function method". It is based on the complex frequency response solution of a single-degree-of-freedom system. During the steady-state vibration of a foundation block, subjected to harmonic vertical excitation with frequency ω, the amplitude of the vibration $A_z(\omega)$ and the corresponding subgrade reaction force $R_z(\omega)$, together with the phase angle between them $\alpha(\omega)$ should be measured. The stiffness and damping coefficients are calculated by the following relations

$$k_z = \frac{R_z(\omega)}{A_z(\omega)}\cos\alpha(\omega) \tag{13}$$

and

$$\xi_z = \frac{R_z(\omega)}{2\omega A_z(\omega)\sqrt{k_z m}}\sin\alpha(\omega), \tag{14}$$

where m = mass of foundation and exciting machine

As the subgrade reaction force and the phase angle between the reaction force and the amplitude of the foundation vibration is difficult to be measured directly, the following equations are given in the Manual for their computation

$$R_z = F_z(\omega)\sqrt{\psi^2(\omega) + 2\psi(\omega)\cos\gamma(\omega) + 1} \quad (15)$$

and

$$\alpha(\omega) = \tan^{-1}\frac{\sin\gamma(\omega)}{\psi(\omega) + \cos\gamma(\omega)}, \quad (16)$$

where $F_z(\omega)$ = exciting force,
$\gamma(\omega)$ = phase angle between exciting force and amplitude of vibration,
$\psi(\omega)$ = $m\omega^2 A_z(\omega)/F_z(\omega)$, ratio between inertia force acting on the soil and exciting force

Using the test data, the values of k_z and ξ_z are computed for frequencies of excitation close to the resonant frequency. They are also listed in Table 1.

The horizontal vibration test was conducted only in the second position of the foundation block, loaded with six R.C. beams (Fig. 2). The dynamic model of the soil-foundation system for horizontal excitation has two-degree-of freedom. Hence, two normal modes of vibration exist. However, only the first mode of vibration was excited. The frequency of the maximum response amplitudes of all measured points of the foundation was 20.48 Hz. It was not possible to excite the second mode as the maximum exciting frequency was 50 Hz.

4 COMPARISON AND DISCUSSION OF RESULTS

Comparing the computed values of the spring constants, given in Table 1, it is evident that the Resonance method and the Transfer function method give approximately the same results. A fairly good agreement between the damping ratios, obtained by Eq.(7) of the Resonance method and Eq.(14) of the Transfer function method can also be noticed. Probably this is due to the fact that both methods use an equivalent lumped parameter model presented by a single-degree-of-freedom system. The only difference is in the solution approach of the equation of motion.

If the subgrade reaction force $R_z(\omega)$ and the phase angle between $A_z(\omega)$ and $R_z(\omega)$ can be measured directly from the test, then it will be advisable to apply the Transfer function method. Otherwise, the Resonance method can be recommended.

The calculated by Eq.(2) spring constants versus static pressure level for both positions of the foundation are plotted in Fig. 5. It can be seen that the equivalent effective spring constant of the soil is dependent on the static compression in the contact area between foundation and soil. In fact the pressure levels in this study are comparatively low and a verification is needed for higher pressure levels.

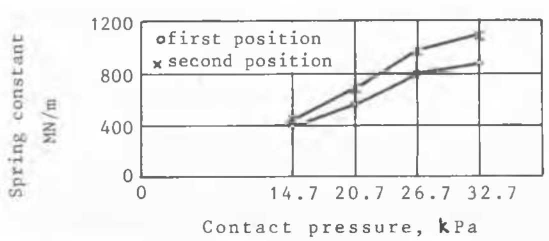

Figure 5. Spring constant-versus-contact pressure

Considering the test data for the damping ratio it can be seen that there is no indication of any relation between contact pressure and damping value (Table 1). The calculated values of ξ by Eq.(7) and Eq.(14) are approximately the same, but they are quite different from those obtained by Eq.(5) and Eq.(11). It is rather difficult to explain the pronounced differences between the values determined by Eq.(5) and Eq.(7). The values of ξ, estimated by the bandwidth method, are several times smaller than those of the same quantity, determined by the magnification effect at resonance frequency. The experimentally obtained response curves are comparatively narrow (see Fig. 3). This leads to small damping values.

All measured points of the foundation vibrated simultaneously during its steady-state vertical vibration. However, the foundation block is not infinitely rigid and it behaved as an elastic plate on an elastic half-space.

5 CONCLUDING REMARKS

Field methods give valuable information for verification of soil-foundation dynamic models and for improvement of practical design methods.

It was found that the equivalent spring constants of the tested soil increase as the contact pressure level increases. More data are needed to clarify that point, particularly for higher pressure levels.

Another important problem concerns the value of damping ratio. The data obtained by the different methods are rather eratic.To explain the marked differences of the damping values further study is necessary.

Additional valuable data are expected to be obtained after construction of the turbine foundation and performance of full-scale vibration tests.

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